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CHARACTERISTICS OF AC-ECM SIGNALS OBTAINED BY USE OF THE VESTFONNA ICE CORE, SVALBARD

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Abstract: AC-ECM measurements of the Vestfonna ice core were carried out under the following conditions: at −12, −17, −22 and −27°C under 1 MHz; at −22°C under frequencies from 300 kHz to 1 MHz. The relationship between conductance measured with AC-ECM and acidity was linear. It is considered that salt impurities also affect to the AC-ECM signals. However, we focus on the effect of acidity, because it is known that the effect of acid on the a.c. conductance is 3.6 times as large as that of salt from DEP analysis of the Dolleman ice core. The intercept of the linear regression is coincident with the conductance of pure ice; at −23°C, it is 3.6 nS. The gradient, conductance increases raised acid, is 0.70 nS l/μmol at −23°C. The gradients at four temperatures were well fitted with the Arrhenius equation and activation energy is 24.8 kJ/mol. Activation energy obtained from this study, the Dolleman ice core and acid-doped ice agree with each other within the error range. The conductance at −22°C increases monotonically from 300 kHz to 1 MHz. This tendency is not caused by the system but by impurities in the specimen. The ratio between the conductance at 300 kHz and at 1 MHz is 0.845. This can not explain with one Debye dispersion. These results add basic knowledge for radio-echo soundings, especially at percolation zone in the ice cap.

1. Introduction

Radio echo sounding of ice sheets is a powerful method to study the three dimensional internal structures of ice sheets (*e.g.* ROBIN *et al.*, 1969; BOGORODSKY *et al.*, 1985). To determine the internal structures of ice sheets from radio echoes, it is necessary to know their characteristics. Studies on dielectric properties of ice which contains acid impurity (MOORE and FUJITA, 1993) and dielectric anisotropy of ice (FUJITA *et al.*, 1993) have indicated that the Fresnel reflection coefficient of internal layers depends on the frequency (FUJITA and MAE, 1994): the coefficient due to acidity changes is inversely proportional to the frequency; the coefficient due to fabric changes is constant with the frequency, from VHF to microwave frequencies. Thus, it is indicated that acidity changes are the predominant cause of internal reflections at low frequencies (lower than about 60 MHz).

However, this result on frequency dependence of the coefficient takes only loss tangent increases due to acidity changes into account. From 1 kHz to 30 MHz, the complex permittivity of acid (H_2SO_4, HNO_3 and HCl)-doped ice was measured in order to form a basic data set for radio echo soundings of ice sheets and dielectric analysis of ice cores (MATSUOKA *et al.*, 1996). This experiment showed that the Fresnel reflection coefficient of hi-acidity layers is affected mainly by conductivity increases, and that the effect of permittivity increases is about 0.4 dB in the HF range (MATSUOKA *et al.*, 1996). This is below 1% of the value of the coefficient. Therefore, to develop a new ice radar which is made to detect acidity changes in ice sheets, it is important to investigate the relationship between acidity and electrical a.c. conductivity of ice cores in this frequency range.

There are two techniques to measure a.c. conductivity of ice cores: AC-ECM (Alternating Current-Electrical Conductivity Measurement) and DEP (DiElectric Profiling). AC-ECM is a technique to measure the conductance of an ice core surface with electrodes similar to that of ECM (Electrical Conductivity Measurement; HAMMER, 1980), and the conductance linearly depends on ice core conductivity (SUGIYAMA *et al.*, 1995). DEP is a technique to measure the conductivity with curved plate electrodes which sandwich the ice core (MOORE and PAREN, 1987). Hence, both techniques collect similar signals. On the other hand, the upper limit frequency of AC-ECM is 1 MHz, near the radio frequencies, and that of DEP is 300 kHz. Therefore, from the aspect of radar application, AC-ECM is more useful than DEP.

Although many studies of dielectric properties of ice cores have been carried out, there is little knowledge of dielectric properties of ice which has melted since deposition. This knowledge is important to interpret radar echoes, especially from the percolation zone in the ice cap. At the top of the Vestfonna ice cap (21°02′E, 79°58′N, 600 m a.s.l.) in Svalbard, a 210 m deep ice core was taken in the summer of 1995 by the Japanese Arctic Glaciological Expedition (JAGE) 1995. According to the stratigraphical analysis, it was observed that many melt-layers existed in the core. Information from the AC-ECM measurements of this core provides basically knowledge on radio echo soundings in the percolation zone.

In this paper, we present the results of AC-ECM measurements of the Vestfonna ice core. First, we show the relationship between AC-ECM signals and acidity. After that, we discuss the temperature dependence of conductance increases raised from acid existence, and compare the result with an Antarctic ice core and laboratory grown acid-doped ice. Finally, we present the frequency dependence of AC-ECM signals and discuss the possible mechanisms.

2. Experiments

The measurement system is consists of an AC-ECM electrode and a precision LCR meter (HP-4285A). The distance between electrodes is 9 mm. The LCR meter is controlled by a computer and data are stored in it with a GP-IB. The description of AC-ECM method was described in detail by SUGIYAMA *et al.* (1995).

We used the Vestfonna (Svalbard) ice core from 5.73 to 7.98 m and from 9.76 to 15.32 m for this study. Mean major ion concentrations and pH are shown in Table 1. Stratigraphy, density and ECM signals of this part are shown in Fig. 1.

Table 1. Chemical components of two parts of Vestfonna ice core. The concentration of ions are in the unit of micro mole per little.

Species	Mean concentration (μmol/l)	
	5.73–7.98 m depths	9.76–15.32 m depths
Cl^-	113.7	0.58
NO_3^-	1.51	1.61
NO_4^{2-}	3.35	1.10
Na^+	29.41	0.52
K^+	84.07	1.53
Mg^{2+}	3.65	0.72
Ca^{2+}	1.52	0.61
pH	5.37	5.22

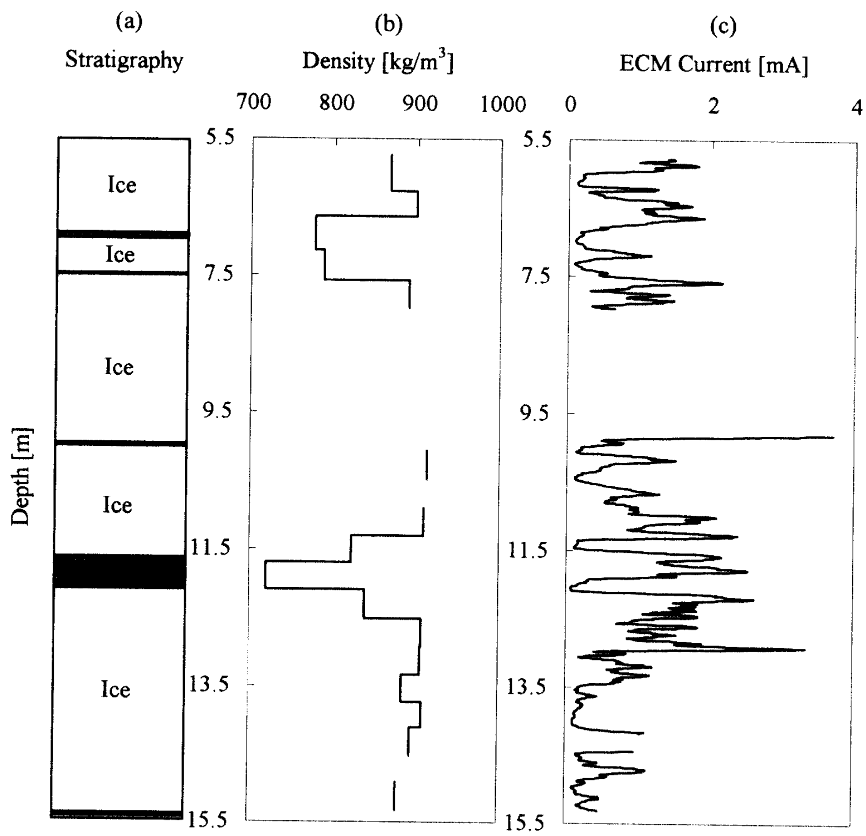

Fig. 1. Stratigraphy (a), density (b) and ECM current (c) of two parts of the Vestfonna ice core. Shadow parts of the stratigraphy are firn; the rest is ice.

AC-ECM data are obtained at 1 cm intervals. As the core is from shallow depth (less than 15 m), some parts are firn and others are ice both of which include many air bubbles. In the firn part, electrodes penetrate into the firn and the contact area between the electrodes and ice seemed to increase compared to the ice. As a result, as the measured conductance is proportional to the contact area, the AC-ECM signals increased. On the other hand, in the ice part, sometimes the electrodes did not contact cores well and the signals decreased. To eliminate the effect of contact area changes, the measurements were carried out two times for each core at a given frequency and temperature. In the firn part and ice part, smaller or larger signals are used for analysis, respectively. The mean difference between these two signals was 1.4 nS.

In this experiment, two sets of measurements were carried out: at four temperatures, -12, -16, -21 and -27°C, at frequency 1 MHz; at eight frequencies from 300 kHz to 1 MHz at 100 kHz intervals at temperature -21°C. For the first trial, we discuss the relationship between AC-ECM signals and acidity, and the temperature dependence of the relationship. For the second trial, we discuss the frequency dependence of AC-ECM signals.

3. Results and Discussion

3.1. Relationship between AC-ECM signals and acidity

In Fig. 2, we show the relationship between conductance measured with AC-ECM, G, and acid concentration at -21°C under a constant frequency of 1 MHz for one example. The conductance is assumed to lineally depend on the acid concentration in molarity. Thus,

$$G = \mu_{acid}[\mathrm{acid}] + A. \tag{1}$$

From now on, [acid] represents the concentration of acid in molarity. At -21°C, μ_{acid} is 0.70 ± 0.14 nS l/μmol and A is 3.6 ± 0.9 nS with the standard error. In order to

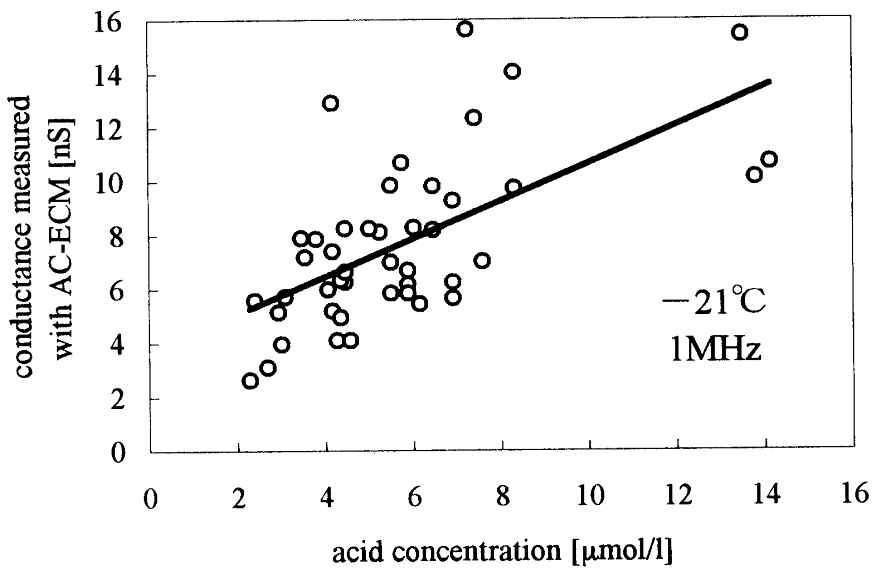

Fig. 2. Relationship between conductance measured with AC-ECM and acid concentration at −21°C under 1 MHz. Conductance measured at 1 cm intervals is averaged according to the chemical analysis resolution. The line is a linear regression line.

compare these data to pure ice, AC-ECM measurements of pure ice were also carried out under the same conditions. Two pure ice specimens were made from distilled deionized water. The mean conductance of pure ice is 3.5 ± 0.5 nS. The conductance of pure ice is coincident with A of eq. (1). Therefore, the constant, A, represents conductance of pure ice.

The scatter in values obtained from eq. (1) is attributed to the variation of salt impurity concentration. MOORE *et al.* (1992) claimed that the a.c. conductivity of ice core is affected by both acid and salt impurity. Studies on the Dolleman ice core with the DEP technique showed that the conductivity, σ, is a linear combination of the molarities of acid and salt impurity plus a constant, *i.e.*

$$\sigma = \nu_{acid}[\text{acid}] + \nu_{salt}[\text{salt}] + B. \tag{2}$$

ν_{acid} and ν_{salt} of the Dolleman ice core are 1.43 and 0.39 mS/m μmol/l respectively at -22°C. To consider the effect of salt impurities, it is necessary to calculate the concentration under assumptions. MOORE *et al.* (1992) assumed that salt was only from the sea with the standard marine ratio. If the ice melted once after the deposition, it has to be also assumed for the calculation that the characteristic of ions released by melting are not different for different ions and the ion composition ratio does not change. The knowledge of the first assumption is poor and the second is not supported by some studies (*e.g.* DAVIES *et al.*, 1982). Hence, it is ambiguous to estimate the concentration of the salt impurities. Moreover, the effect of acid is 3.6 times as large as that of salt impurity in the Dolleman ice core (MOORE *et al.*, 1992). Therefore, we do not focus on the effect of salt impurities here and discuss the characteristics of μ_{acid}, only. Regressions are carried out at four temperatures and μ_{acid} values are obtained. In the following, we discuss the temperature dependence of μ_{acid}, conductance increases due to the acid.

3.2. *Temperature dependence of the relationship between AC-ECM signals and acidity*

Figure 3 shows the temperature dependence of μ_{acid}, which is assumed to fit the Arrhenius equation:

$$\mu_{acid} \propto \exp\left(-\frac{E}{kT}\right), \tag{3}$$

where k is the Boltzmann constant and T is the absolute temperature. E, activation energy of μ_{acid}, is 24.8 ± 8.8 kJ/mol with standard error at 1 MHz.

SUGIYAMA *et al.* (1995) showed that the conductance measured with AC-ECM linearly depends on conductivity of ice measured with parallel plate electrodes. The dependence was examined at -22°C only; however, we assume that the relationship holds and the proportionality coefficient is constant with temperature, in the temperature range of this study (from -12°C to -27°C). This assumption seems to hold in the temperature range in which the conduction mechanisms remains the same. The temperature dependence of the electrical conduction component arising from acid in this temperature range is well explained by an Arrhenius activation process from around -10°C to minus several tens of degrees Celsius (*e.g.* MOORE and FUJITA, 1993). This means that the conduction mechanisms are the same, hence, this assumption is valid for this temperature range. Under this assumption,

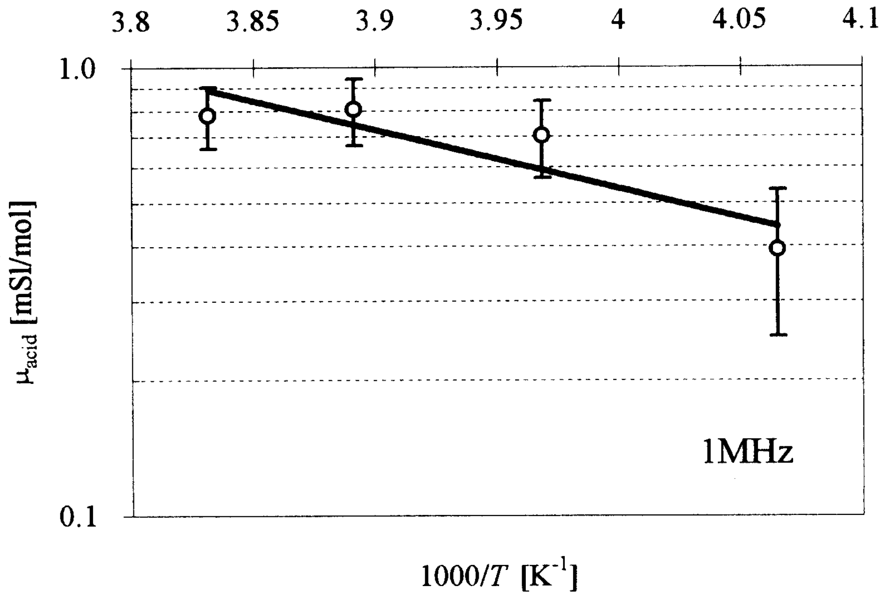

Fig. 3. Arrhenius plot of conductance increases due to the presence of acid, μ_{acid}, at 1 MHz. Error bars indicate the standard error in the linear regression with eq. (1).

$$\sigma = \alpha G, \tag{4}$$

where α is the proportionality coefficient between G and σ. Hence, the σ component due to acid, $\alpha\mu_{acid}$, has the following temperature dependence from eq. (3):

$$\alpha\mu_{acid} \propto \alpha \exp\left(-\frac{E}{kT}\right). \tag{5}$$

In Table 2, we show the activation energies of $\alpha\mu_{acid}$ of this study and of conductivity due to laboratory experiments (MATSUOKA *et al.*, 1996), and ν_{acid} of the Dolleman ice core (MOORE *et al.*, 1992). Table 2 shows that the differences between these activation energies of various specimens are below the error. This suggests that the electrical conduction due to acid in ice cores in percolation zones, polar ice cores and acid-doped ice are the same. This indicates that results from laboratory experiments (MATSUOKA *et al.*, 1996) are valid

Table 2. Activation energy (A.E.) of conductance or conductivity increases raised from molar acid existence. Errors mean standard errors in calculating the activation energy. Note that A.E. obtained in this study and laboratory experiment are calculated with eq. (1) and that of Dolleman ice core is calculated with eq. (2).

	A.E. (kJ/mol)	Frequency	Temperature range	Reference
This study	24.8±8.76	1 MHz	4 points from −12°C to −27°C	—
Dolleman	25.1±2.89	*1	−10°C and −22°C	MOORE *et al.* (1992)
Acid-doped ice*2	21.1±0.841	1 MHz	7 points from −8.7°C to −32.6°C	MATSUOKA *et al.* (1996)

*1 : Measured from 20 kHz to 100 kHz and extrapolated to high frequency. *See* MOORE *et al.* (1992).
*2 : H_2SO_4, HNO_3 and HCl doped, respectively. The acid concentration is from 3.9 to 10.5 μmol/l.

not only for polar regions but also percolation zones.

3.3. Frequency dependence of AC-ECM signals

In Fig. 4, the conductance measured with AC-ECM, G, at 300 kHz is compared to G at 1 MHz. Figure 4 shows that G at 300 kHz is proportional to G at 1 MHz, and the proportionality coefficient is 0.845 ± 0.012 with a 99% confidence interval. This proportional relationship of G is also found in the frequency range from 400 kHz to 900 kHz. The ratio of G at f ($f=300$ kHz to 900 kHz with 100 kHz intervals) to G at 1 MHz is shown in Fig. 5. Figure 5 indicates that the conductance from 300 kHz to 1 MHz increases monotonically.

In order to determine the frequency dependence of the AC-ECM system itself, AC-ECM measurements of pure ice were carried out at -22°C from 300 kHz to 1 MHz. The mean value of 14 independent measured values at each frequency in this frequency range was 3.1 nS (*cf see* Fig. 2 for the measured G of this core). The standard deviation among 14 measured values at each frequency is as same as the frequency variation of the measured values. For example, G at 300 kHz is 2.8 ± 0.5 nS and G at 1 MHz is 3.5 ± 0.5 nS. Therefore, a large part of the conductance increase shown in Fig. 4 is considered to be due to the dielectric characteristics of ice cores.

When the dielectric properties can be described by Debye's theory, conductivity is written as follows:

$$\sigma = (2\pi)^2 \varepsilon_0 f \frac{(\varepsilon_{r0} - \varepsilon_{r\infty})F}{1 + (2\pi)^2 F^2}, \qquad (6)$$

where σ is conductivity, ε_0 is the permittivity of free space, ε_{r0} is static permittivity, $\varepsilon_{r\infty}$ is the limiting high-frequency permittivity, f is frequency and F is f divided by the

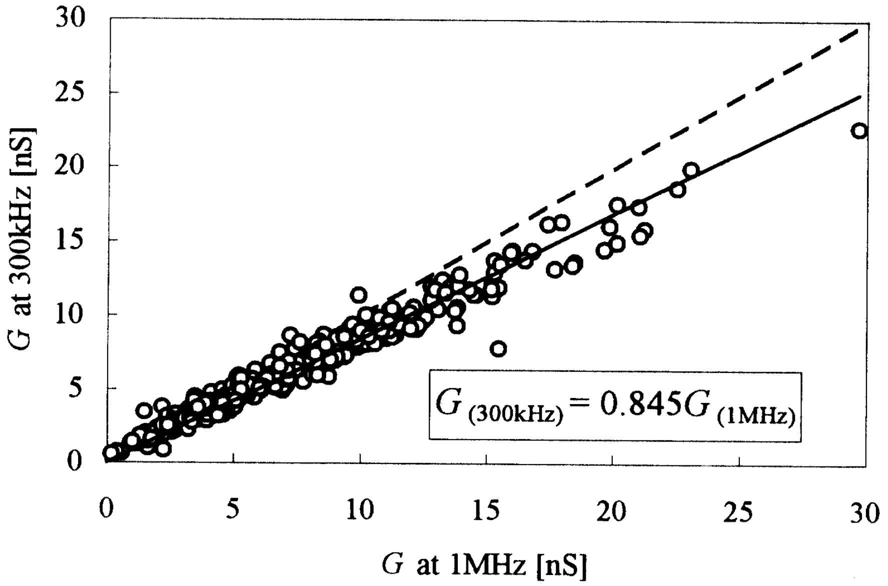

Fig. 4. Relationship of conductance measured at 1 MHz and at 300 kHz, at -22°C. A solid line is a linear regression line with fixed intercept zero, and the gradient is 0.845. The gradient of a dashed line is 1.

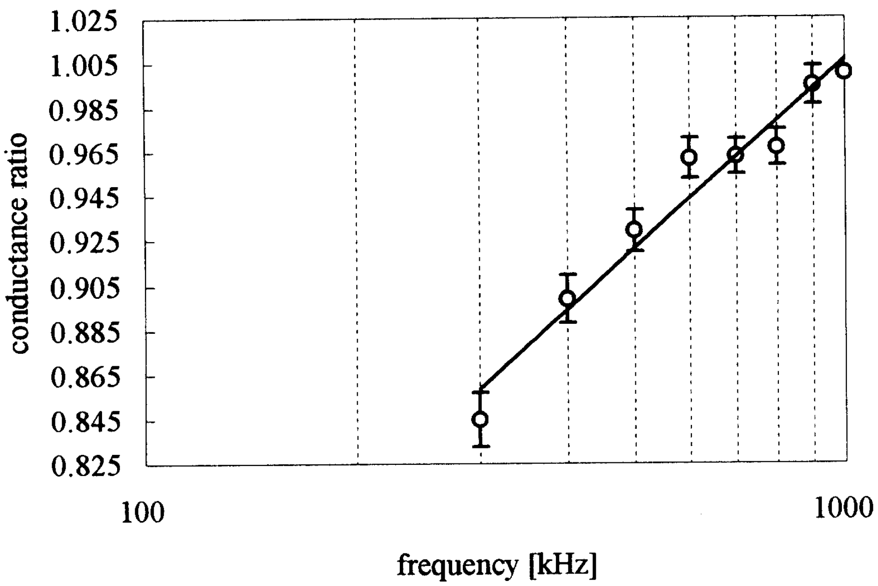

Fig. 5. Frequency dependence of conductance. The vertical axis is the ratio of conductance at each frequency to that at 1 MHz. Error bars indicate the 99% confidence interval. The line is a legalistic regression line.

relaxation frequency f_0. When $(2\pi)^2F^2 \gg 1$, σ is constant with frequency. Equation (6) shows that, when f is larger than 2.5 times f_0, the σ variation with frequency is less than 1% of σ, in the case of ice. We denote the frequency as f_{limit}. f_0 of the Dolleman ice core is less than about 60 kHz (*see* Fig. 1 in MOORE *et al.*, 1989). If we assume that f_0 is 60 kHz, f_{limit} is 150 kHz. Hence, it is considered that the conductance increases observed in this core from 300 kHz to 1 MHz cannot be explained by the mono-dielectric process which is described by Debye's theory. This indicates that ice which contains impurity has multiple dispersions in this frequency range.

4. Conclusions

AC-ECM measurements of Vestfonna ice core was carried out at -12, -17, -22 and -27°C under 1 MHz. The relationship between conductance measured with AC-ECM and acidity is linear. The intercept value of the conductance is coincident with the conductance of pure ice. Conductance increases raised from acid existence, at four temperatures were well fitted with the Arrhenius equation and activation energy is 24.8 kJ/mol. Activation energies of this study, Dolleman ice core and acid-doped ice are coincident with each other in the error range. This indicates that electrical a.c. conduction mechanisms of sub-polar ice, polar ice and laboratory grown ice are the same. The conductance at -22°C increases monotonically from 300 kHz to 1 MHz. This tendency occurred from impurity existence.

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References

BOGORODSKY, V.V., BENTLEY, C.R. and GUDMANDSEN, P.E. (1985): Radioglaciology. Dordrecht, D. Reidel, 254 p.

DAVIES, T.D., VINCENT, C.E. and BRIMBLECOMBE, P. (1982): Preferential elution of strong acids from a Norwegian ice cap. Nature, **300**, 161-163.

FUJITA, S and MAE, S. (1994): Causes and nature of ice-sheet radio-echo internal reflections estimated from the dielectric properties of ice. Ann. Glaciol., **20**, 80-86.

FUJITA, S., MATSUOKA, T., MORISHIMA, S. and MAE, S. (1993): The measurement on the dielectric properties of ice at HF, VHF and microwave frequencies. Proceedings of International Geoscience and Remote Sensing Symposium (IGARSS '93), Tokyo, **3**, 1258-1260.

HAMMER, C.U. (1980): Acidity of polar ice cores in relation to absolute dating, past volcanism, and radio echoes. J. Glaciol., **25**, 359-371.

MATSUOKA, K., FUJITA, S., MATSUOKA, T., ISHIDA, T., HONDOH, T. and MAE, S. (1996): Measurements of the complex permittivity of acid-doped ice from 1 kHz to 30 MHz—New data set for developing ice radar and dielectric analysis of ice cores—. Proc. NIPR Symp. Polar Meteorol. Glaciol., **10**, 25-35.

MOORE, J.C. and FUJITA, S. (1993): Dielectric properties of ice containing acid and salt impurity at microwave and low frequencies. J. Geophys. Res., **98**, 9769-9780.

MOORE, J.C. and PAREN, J.G. (1987): A new technique for dielectric logging of Antarctic ice cores. J. Phys., **48**(3), c1-155-c1-160.

MOORE, J.C., MULVANEY, R. and PAREN, J.G. (1989): Dielectric stratigraphy of ice: A new technique for determining total ionic concentrations in polar ice cores. Geophys. Res. Lett., **16**, 1177-1180.

MOORE, J.C., WOLFF, E.W., CLAUSEN H.B. and HAMMER, C.U. (1992): The chemical basis for electrical stratigraphy of ice. J. Geophys. Res., **97**, 1889-1896.

ROBIN, G. de Q., EVANS, S. and BAILEY, J.T. (1969): Interpretation of radio echo sounding in polar ice sheets. Philos. Trans. R. Soc. London, Ser. A, **265**, 437-505.

SUGIYAMA, K., FUJITA, S., SUEOKA, S., MAE, S. and HONDOH, T. (1995): Preliminary measurement of high-frequency electrical conductivity of Antarctic ice with AC-ECM technique. Proc. NIPR Symp. Polar Meteorol. Glaciol., **9**, 12-22.

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